International Journal on Advanced Science Engineering Information Technology

Vol.10 (2020) No. 1
ISSN: 2088-5334

Numerical Study: Effect of Various Link Length to Lateral Force in Eccentrically Braced Frame

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***Abstract*— Eccentrically Braced Frame (EBF) is an excellent steel frame system for resisting earthquake forces. This frame shows good performance in terms of stiffness and has excellent ductility. When it is subject to a severe seismic event, the links undergo inelastic deformations and become the primary source of energy dissipation. However, the performance of EBF is strongly influenced by the length of the links that are an essential part of the EBF system. Links should be limited not be too short or too long because it relates to the stiffness and ductility of the frame. The study of EBF on the 80-90s also limits the ratio both of e/L not exceed 0.5 and the diagonal brace angle between 40°- 60°. This research will review the influence of the length of the links varied from the e/L ratio of 0.005 to 0.38. This variation will divide the links into three types of yielding, i.e., the short link, intermediate link with shear dominance, and intermediate link with bending dominance. In this study, the behavior of various link lengths on Eccentrically Braced Frame will be evaluated using finite element analysis using MSC Patran and Nastran. The structure is modeled as a one-dimensional D-Braced EBF type that is given static monotonic load with displacement control. The results obtained in the form of load-displacement curves which will be analyzed in strength and ductility. In addition, an ultimate load normalization curve will be generated to obtain the load pattern for the various link length. The curve shows that the ultimate load on the EBF will decrease if there is an increase in link length. The significant decrease occurs when e/L > 0.2.**

***Keywords*— eccentrically braced frame; various link length; stiffness; ductility.**

I. INTRODUCTION

The structure is expected to be strong in accepting loads and not collapse when receiving a large rare load like winds and earthquakes. The Moment Resisting Frame (MRF) is a type of frame that is commonly used in steel construction. It has good ductility, but the stiffness tends to be small. Concentrically Braced Frame is a type of braced frame with a high stiffness but less ductile. Eccentrically Braced Frame (EBF) is a structural steel frame system that has good ductility and high stiffness in receiving lateral forces, [1], [2], [3]. EBF has a combination of MRF and CBF properties that meet the criteria of the structure in terms of strength, stiffness, and ability to absorb dissipation energy [4].

The innovative frame "eccentric system" was first introduced by Fujimoto et al. (1972) and Tanabashi et al. (1974) in Japan. Then in 1978, Popov et al. at the University of California conducted an experimental test on this eccentric frame system. This system is named eccentric because it is intentionally designed eccentricity on the system, usually in a beam segment. Furthermore, various reviews and studies on the EBF system are still being developed until now [5].

The characteristics of EBF systems are to have at least one diagonal brace connected eccentrically from column to the beam, as well as link elements that are part of the beam that connected eccentrically to the brace (Fig 1.).

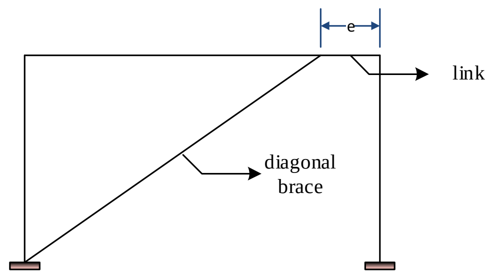


Fig. 1. Eccentrically Braced Frame

The eccentricity between brace and beam serves to prevent buckling in the brace system during extreme loads. As a result, a better dissipation energy curve will be gain than a portal with bracing, which is concentrically connected. With the brace connected to columns and beams, axial loads are distributed through the brace into shear forces in columns and bending moments on the beam. The column, beam and brace elements must design as a strong element, while the link element is the weakest element of the structure. The link serves as a passive control to prevent buckling on brace [6]. When it is subject to a severe seismic event, the links undergo inelastic deformations and become the primary source of energy dissipation [7].

The ability of the EBF system to receive seismic loads can also be seen from the hysteresis curve, which shows how the frame rigidity increases with no pinch due to diagonal bracing is designed as a strong element and does not buckle [8].

However, this phenomenon is strongly influenced by the length of the link (e) used on the frame [9]. Since the EBF system is a combination of Moment Resisting Frame (MRF) and Concentrically Braced Frame (CBF) systems, the link performs as the MRFs system and if e = L then the frame will act like CBFs system if e = 0 [1]. With proper selection of link lengths, then bracing will be effective in increasing the stiffness value as well as being able to receive large inelastic deformations.

Based on the scheme of the effect of the e/L ratio, link performance would be excellent if using an e/L ratio < 0.5 and bracing angle should be kept less than 60□ [2]. The distribution of internal forces (Fig. 2) on link elements affects the failure behavior of links [10]. If analyzed using Simple Plastic Analysis (SPA) approach, it can be seen that the relationship between the length of the link and the moment and shear value distribution if $e < 2M_p/V_p$ then the link will perform pure shear ($V=V_p$, $M< M_p$) and if e □□$2M_p/V_p$ then the link will be bending ($V<V_p$, $M=M_p$). That means by using the ratio of e / L < 0.5, the link can act as shear, bending, or both.

The classification of links based on the various length are [11] :

a. Short link, $e < 1.6\ M_p/V_p$
Yielding is dominated by shear.

b. Intermediate link (shear dominance) , $1.6\ M_p/V_p < e < 2.6\ M_p/V_p$)
Yielding is a combination of shear and bending

c. Intermediate link (bending dominance) $2.6\ M_p/V_p < e < 5\ M_p/V_p$
Yielding is a combination of shear and bending

d. Long link $e > 5\ M_p/V_p$
Yielding is dominated by bending.

The shear and bending limit of the link element is determined by the following equation [12]:

$$M_p = F_y.Z \quad (1)$$

$$Vp = 0.6\ F_y.A_w \quad (2)$$

where,
M_p = fully plastic moment of the section
V_p = fully plastic shear capacity
F_y = yield strength
Z = plastic modulus
A_w = web area

Ghobarah (1991) began to examine the effect of link length on EBF performance. The results show that the strength, stiffness, and energy absorption capabilities of short links are considerably reduced compared to longer links [16]. There have been many studied that recommend the use of short links on the EBF because it has the most significant capacity for inelastic deformation [13], [14]. Another substantial difference between a short link and long links are longer links giving more open areas in architectural [14].

The behavior of links with $e > 1.6\ M_p/V_p$ is a combination of shear yielding on the web and flexure yielding on the upper flange of both ends of the link. The slenderness ratio is a factor affecting the strength degradation in the long link.

Nevertheless, several studies have been conducted to improve the performance of long links with the addition of stiffener at the cross-section of the web of the link that provides a tendency to change the behavior of the link from yielding is dominant by bending to yield in shear [11].

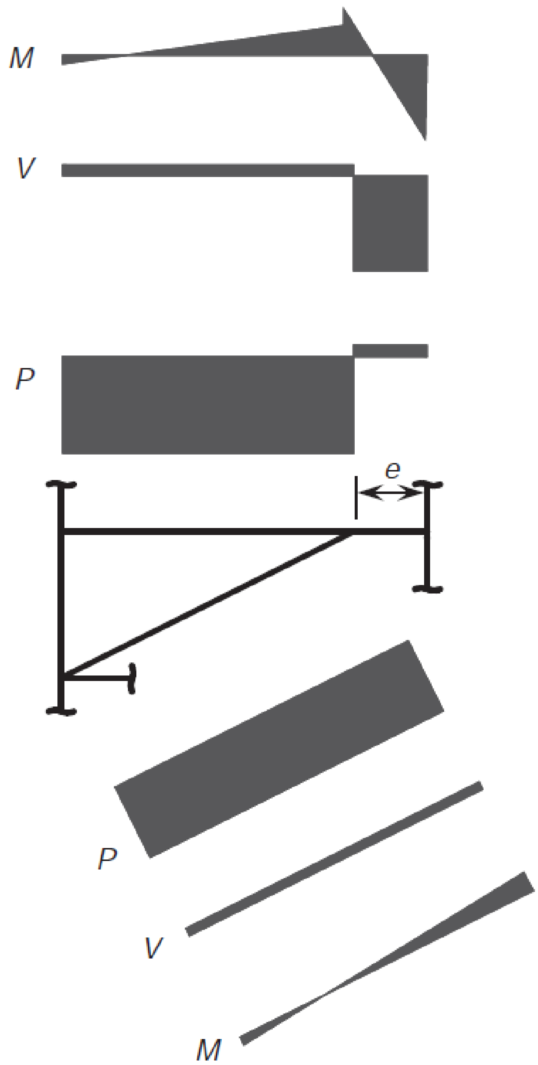


Fig. 2. Internal forces distribution in EBF (adopted from Bruneau, Uang, & Sabelli, 2011)

An analysis of 23 link length variations has been carried out to get a better understanding of the effect of the link length on EBF behavior. The length of the link analyzed is limited by the value of the e ratio of 0.039 M_p /V_p to 3.11 M_p /V_p. The result will be used to analyze the effect of the link length (e) to strength, displacement, ductility, and type of yield on EBF.

II. Material and Method

A. Model Structure

A one-story frame with a beam length of L = 6000 mm and a column height of H = 3500 mm was used as a model in this study. The dimension of the cross-section of the beams and columns used in WF 400.200.8.13 and the brace is 200.100.5.5.8. Link is a model as a D-Braced EBF type with the variation of link length. Web stiffener is not modeled in this study.

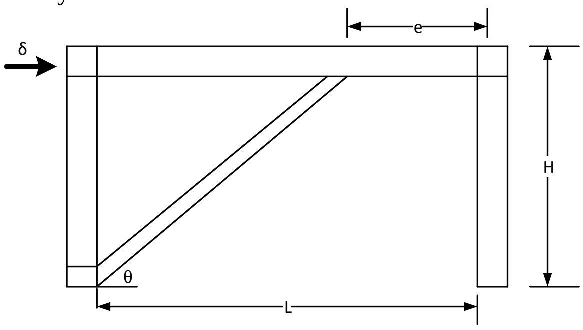


Fig. 3. Structure model- a D-Braced Eccentrically Braced Frame

There are 23 link length variations (Table I – III) with the ratio of e = 0.039 M_p/V_p to e = 3.11 M_p/V_p.

TABLE I
Variation of Short Link Length

ID. No	Link length (e) (mm)	e ratio	θ
1	29	0.039	59.6
2	132.5	0.178	59.2
3	236	0.318	58.7
4	339.5	0.457	58.3
5	443	0.597	57.8
6	546	0.735	57.3
7	650.1	0.876	56.8
8	753.6	1.015	56.3
9	857.2	1.155	55.8
10	960.8	1.294	55.2
11	1064.3	1.434	54.7
12	1167.9	1.573	54.1

TABLE II
Variation of Intermediate Link Length
(1.6 MP/VP < e < 2.6 MP/VP)

ID. No	Link length (e) (mm)	e ratio	θ
13	1271.6	1.713	53.5
14	1375.2	1.852	52.9
15	1478.2	1.991	52.3
16	1582.5	2.132	51.6
17	1686.2	2.271	50.9
18	1789.9	2.411	50.3
19	1893.7	2.551	49.6

TABLE III
Variation of Intermediate Link Length
(2.6 Mp/Vp < e < 5 Mp/Vp)

ID. No	Link length (e) (mm)	e ratio	θ
20	1997.4	2.690	48.8
21	2101.2	2.830	48.1
22	2205	2.970	47.3
23	2308.8	3.110	46.5

B. Model of Material

Using BJ 37 steel with 240 MPa yield strength, 370 MPa ultimate strength, 2G10^{5} MPa modulus elasticity, 8G10^{4} MPa shear modulus, and 0.3 Poisson ratio.

C. Model Finite Element

The structure model will analyze using finite element software MSC Patran and Nastran student version. The element used is a shell element of a structured element modeled as a finite element of a QUAD4 plate with meshing elements, as shown in Fig. 3. In the beam-column connection and diagonal brace - the beam element is connected by the node. Connection type not modeled in this study.

D. Load

Static monotonic loads are provided with displacement controls at the beam-columns connection (Fig.3). The load is given in the lateral direction and allowed to move in the transverse direction. A Static monotonic load is a non-linear static analysis where the effect of an earthquake on a structure is modeled as static loads at the center of mass of the story. The type of static monotonic load used in this analysis is displacement control which is given incrementally by increased the displacement until the structure reaches the ultimate load.

III. Result and Discussion

Numerical analysis is performed on three yielding criteria on link:

a. Short link , e < 1.6 Mp/Vp (model no. 1-12),
b. Intermediate link, 1.6 Mp/Vp < e < 2.6 Mp/Vp (model no. 13-19),
c. Intermediate link, 2.6 Mp/Vp < e < 5 Mp/Vp (model no. 20- 23).

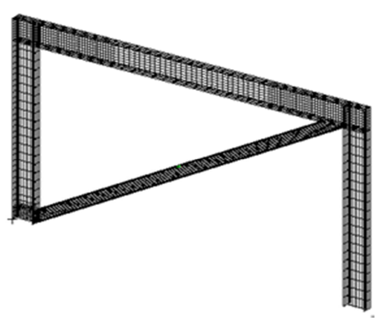


Fig. 4. Model Finite Element

A. Load – displacement relationship

Based on the results of numerical testing, it can be seen the load-displacement relationship on a variety of link lengths are:

1) Short link ,e < 1.6 Mp/Vp: Load vs. the displacement curve patterns, as shown in Figure 5, can be analyzed as two groups of short links. If the length of the short link is less than 0.8 M_p/V_p (Model 1 -6), then the yield displacement value tends to be 9,992 mm - 9,995 mm (Table IV). If the short link length is 0.8 M_p/V_p < e < 1.6 M_p/V_p (Model 7 – 12), the yield displacement occurs at 11.511 mm - 13.029 mm.

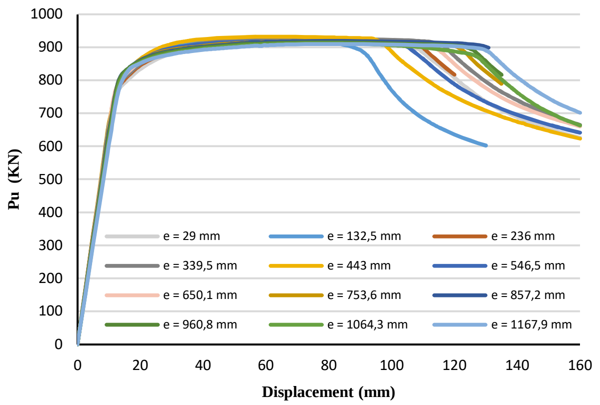


Fig. 5. Load – displacement relationship for shear link

By using a link length of 0.8 M_p/V_p < e < 1.6 M_p/V_p, yield displacement is increased by 15% - 33%. Conversely, the ultimate displacement value tends to decrease. When the short link length is < 0.8 M_p/V_p, the ultimate displacement range is between 55,589 mm - 74,618 mm and if using a short link with 0.8 M_p/V_p < e <1.6 M_p/V_p, the ultimate displacement value is between 75,427 mm - 84,746 mm.

TABLE IV
SHORT LINK ANALYSIS RESULTS

No.	e (mm)	Pu (KN)	δy (mm)	δu (mm)	Ductility
1	29	929.206	9.992	72.492	7.255
2	132,5	921.135	9.994	55.589	5.562
3	236	924.578	9.992	72.707	7.276
4	339,5	926.281	9.993	74.618	7.467
5	443	931.557	9.992	63.205	6.326
6	546,5	917.613	9.995	66.395	6.643
7	650,1	913.159	11.511	75.427	6.553
8	753,6	917.505	12.904	77.194	5.982
9	857,2	918.665	12.957	82.875	6.396
10	960,8	914.436	13.002	81.027	6.232
11	1064,3	911.411	13.028	77.953	5.984
12	1167,9	909.836	13.029	84.746	6.504

Ductility values were obtained at 5,562 - 7,467 for short link lengths less than 0.8 M_p/V_p and 5,982 - 6,553 for short link lengths 0.8 M_p/V_p <e <1.6 M_p/V_p. The maximum ductility value is 7.467 when the link length is less than 0.8 M_p/V_p, and the minimum ductility value is 5,562 for the short link length 0.8 M_p/V_p <e <1.6 M_p/V_p with the average ductility value is 6,514.

2) Intermediate link, 1.6 Mp/Vp < e < 2.6 Mp/Vp: The load vs. displacement curve for the intermediate link 1.6 Mp/Vp < e < 2.6 Mp/Vp indicates that if the link length <1.9 M_p/V_p (Model 13-14) then it behaves like a short link.

The yield displacements value for model no. 13 and 14 are 13,025 mm, and 13,021 mm, with the ultimate displacements, are 86,75 mm and 65,393 mm. For 1.9 Mp/Vp <e <2.6 Mp/Vp (Model 15-19), the average yield displacement is 13 mm and the ultimate displacements are 25,407 - 47,159 mm. The ductility values obtained in models no. 13 and 14 are still at the interval of ductility values in the short link. Subsequently, if the link length is at 1.9 Mp/Vp < e < 2.6 Mp/Vp, the ductility value will decrease with the maximum and minimum ductility values being 3,625 and 1,954.

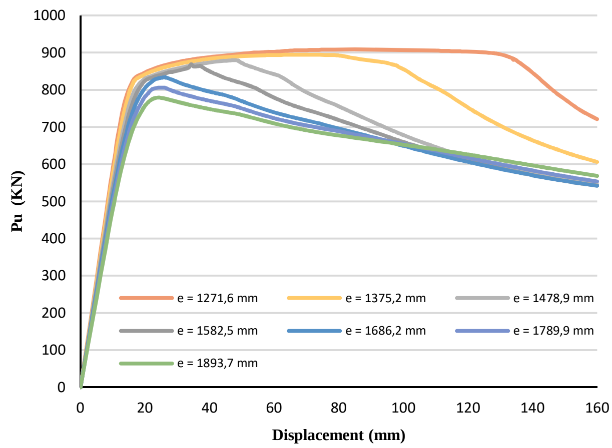


Fig. 6. Numerical failure mode for short link intermediate link (1.6 Mp/Vp < e < 2.6 Mp/Vp)

TABLE V
INTERMEDIATE LINK (1.6 MP/VP < e < 2.6 MP/VP) ANALYSIS RESULTS

No.	e (mm)	Pu (KN)	δy (mm)	δu (mm)	Ductility
13	1271,6	908.518	13.025	86.750	6.660
14	1375,2	895.085	13.021	65.393	5.022
15	1478,9	878.384	13.010	47.159	3.625
16	1582,5	863.141	13.006	38.716	2.977
17	1686,2	833.406	13.006	25.767	1.981
18	1789,9	807.702	13.005	26.094	2.006
19	1893,7	780.173	13.004	25.407	1.954

3) Intermediate link, 2.6 Mp/Vp < e < 5 Mp/Vp: Figure 7 shows the load vs. displacement curve for the intermediate link model (bending dominance). The longer the link, the value of the ultimate load and yield displacement will decrease. The highest ultimate load value obtained at e = 1997.44 mm (model no. 20) is 761.053 KN (Table VI). In contrast, the ultimate displacement value tends to increase if the link length increases. The maximum ductility value in the intermediate link (bending dominance) is 2.418.

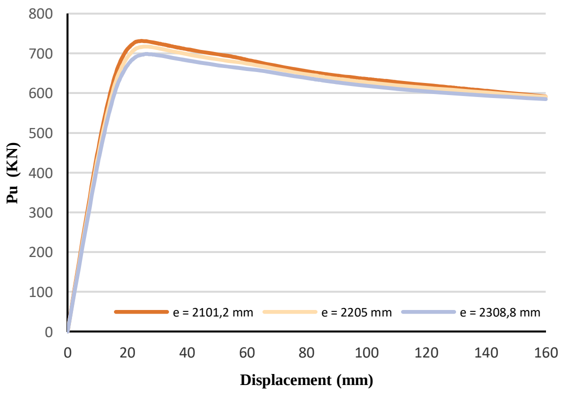


Fig 7. Load – displacement relationship for intermediate link (2.6 Mp/Vp < e < 5 Mp/Vp)

TABLE VI
INTERMEDIATE LINK (2.6 MP/VP < e < 5 MP/VP) ANALYSIS RESULTS

No.	e (mm)	Pu (KN)	δy (mm)	δu (mm)	Ductility
20	1997,44	761.053	13.003	28.211	2.170
21	2101,2	734.396	13.002	28.057	2.158
22	2205	720.413	13.002	31.118	2.393
23	2308,8	702.868	13.004	31.451	2.418

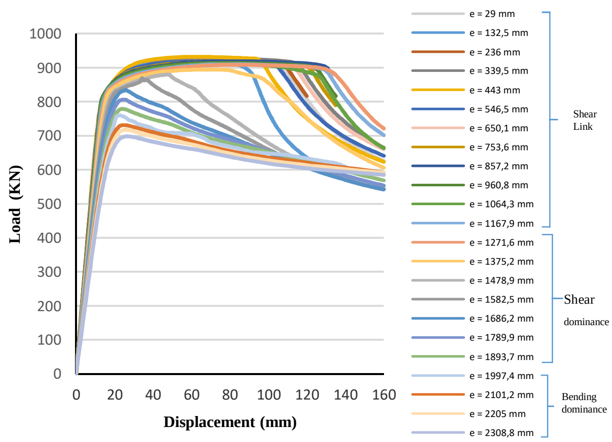


Fig. 8. Load – displacement relationship for various link's length

From the analysis, we get the comparison of load and displacement of each variation, as shown in Fig.8. The curve shows that the addition of link length affects the ultimate load. Increasing link length will decrease the ultimate load value.

In order to see the ratio of the load value to the length of the link, it is normalized with the load when e = 29 mm (e = 0.005 L). The normalization of link length and ultimate load is shown in Fig.9. The curve clearly shows that the length of the link affects the ultimate load value in the EBF system.

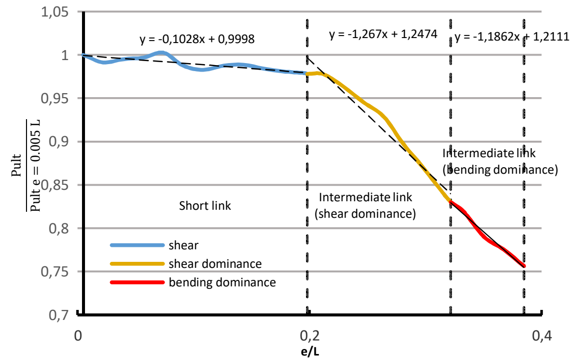
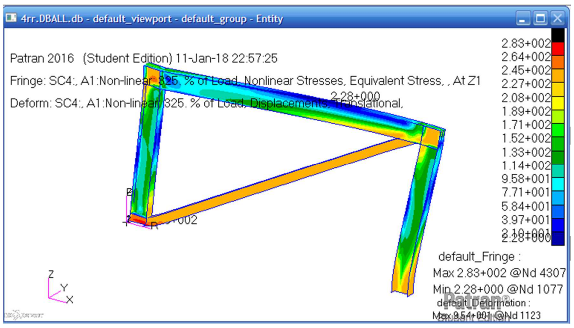


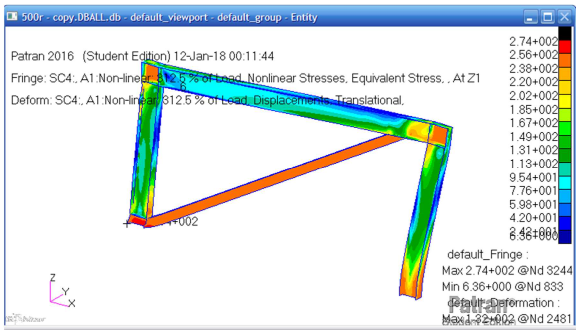
Fig. 9. Ultimate load normalization curve.

B. *Type of Yielding*

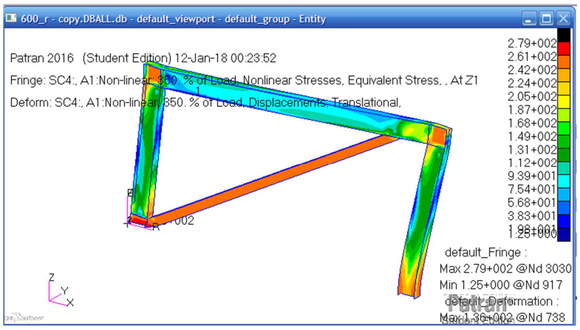
In addition to the comparison of load vs. displacement, various lengths of the link also show changes in the plastic mechanism and the type of yield.



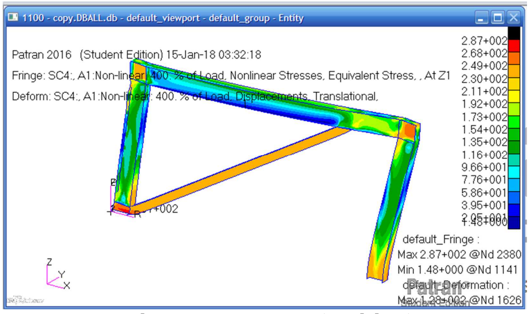
a. e = 132.5 mm (Model 2)



b. e = 546 mm (Model 6)

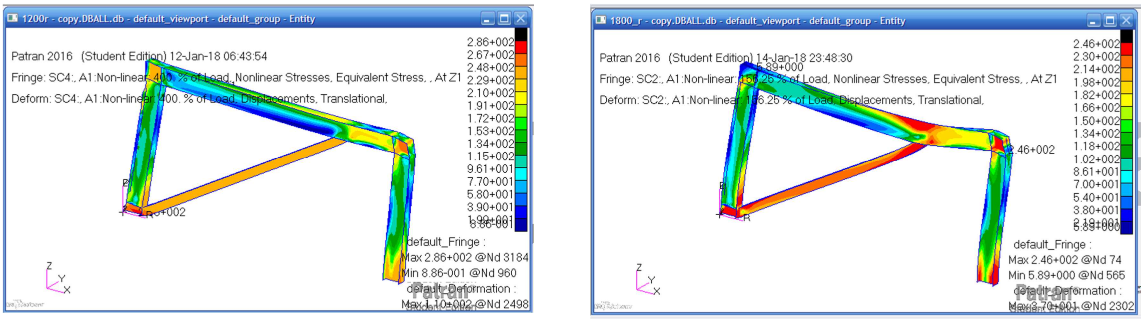


c. e = 650,1 mm (Model 7)



d. e = 1167.9 mm (Model 12)

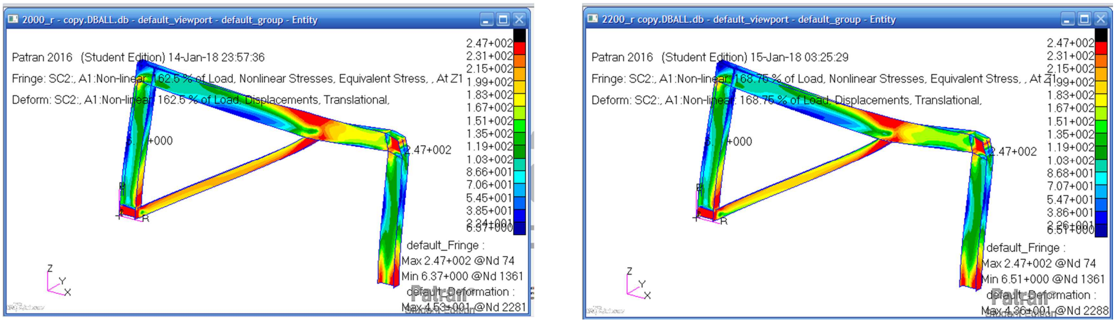
Fig. 10. The numerical failure mode for short link



a. e = 1271.6 mm (Model 13)

b. 1893.7 mm (Model 19)

Fig. 11 . The numerical failure mode for the intermediate link (shear dominant).



a. e = 1997.4 (Model 20)

b. e = 2205 mm (Model 22)

Fig. 12 . Numerical failure mode for the intermediate link (bending dominant)

On links with e <0.8 M_p/V_p (Figure 10 a-b), there is an indication of yielding occurs in the link's web and the connection area of column connection and a diagonal stiffener. This issued by the position of the diagonal stiffener is relatively concentric or close to the beam-column connection.

For link length 0.8 M_p/V_p < e <1.6 M_p/V_p (Fig. 10 c-d), yielding occurs on the web and panel zone located next to the link. The panel zone yield first because there is no web stiffener on the web. The stress concentration transfer from the panel zone to the link. It proves that the web stiffener is a determining factor to ensure yield occurs on the link.

On intermediate links 1.6 M_p/V_p < e < 2.6 M_p/V_p, when e < 1.9 $M_p/V_{p,}$ the link behavior is still like a short link because based on the SPA approach if e < 2 M_p/V_p, the link behaves shear. The short link limit value e < 1.6 M_p/V_p is the critical link length limit value (e_{crit}) recommended by Malley and Popov (1984) and Kasai and Popov (1986a, b) [17]. If the link length is 2 M_p/V_p < e < 2.6 M_p/V_p in Figure. 11 c-f yields occur in the panel zone, part of the link's web and flange, the area around the connection of beam-diagonal stiffener. Yielding that occurs at the flange of the link shows bending failure but is still dominated by shear in the web (shear dominance).

Figure 12. a-c shows that link failure is dominated by bending indicated by yielding that occurs in the upper and lower flange of the link, and only a small part of the web is yield (bending dominance).

IV. Conclusions

The ultimate load on the EBF will decrease if there is an increase in link length. The significant decrease in the ultimate load occurs on the link with dominant shear/bending. The ultimate displacement of the EBF will decrease if there is an increase in link length. The significant decrease in ultimate displacement value occurs in the link with a shear dominant. The ductility of the EBF will decrease if there is an increase in link length. The significant decrease in ultimate displacement value occurs in the link with a shear dominant. Various lengths of the link have changes in the plastic mechanism and the type of yield.

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